

**PATH CALIBRATION AND SOURCE CHARACTERIZATION
IN AND AROUND INDIA**

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ABSTRACT

Regional path calibration of seismic phases is strongly dependent upon the accuracy of hypocentral locations of seismic events. In general, accurate locations and identification of seismic events based on travel time studies require several stations surrounding each event, which is often difficult to achieve especially for events of magnitude M_w 4.5 or less with a very few regional observations. By analyzing seismic events located in central Asia and Tibet, we find that seismic events move significantly away from the EDR or ISC epicentral locations when they are constrained to depths determined by independent means. For the Tibetan experiment, 7 events' locations met the GT10 criteria (Yang and Romney, 1999) and moved from the ISC epicenters significantly; one of them moved by several degrees. Variation from the reference model within the regional distance also adds to these mislocations. Small earthquakes are plentiful in the Indian sub-continent including its neighboring countries, thus rendering seismic monitoring of the region difficult. To this end, we have made literature survey of available crustal structures and developed models which produce remarkable agreement for events recorded at Hyderabad (HYB) to distances of up to 12° . The model consists of two crustal layers with a P_n velocity of 8.0 km/sec. This model produces detailed features observed in regional waveforms from events occurring in the Pokhran test site, central India and Koyna regions. We have also developed a velocity profile from the NW India to NIL using regional waveforms recorded at HYB and NIL from an earthquake that occurred near the Pokhran test site on April 4, 1995. From the teleseismic depth phase (pP) analysis, we estimated the depth of this event at 15 km, shallower than the 18.7 and 21 km depths reported in the REB and PDE bulletins, respectively. We used regional seismograms recorded at HYB to determine its focal mechanism constraining its depth to the teleseismic estimate. Using this focal mechanism and event depth, we then calibrated path towards NIL. This preliminary crustal model from the NW India to NIL consists of four crustal layers; the upper most layer has a thickness of 7 km with velocity relatively lower than the Indian shield region. It also includes a gradient in the upper mantle which helps to account for the strong P_n waves recorded at NIL. The model produces travel times for P, S, Rayleigh and Love waves, including the dispersion recorded in the Rayleigh waves. This model is then used to synthesize explosion seismograms for estimating yield. Knowing better locations and depths of large earthquakes from this area can be useful as they can later be used to calibrate upper-mantle paths towards the NW India and Pakistan. In general, we found that the depths of the events are shallower than the depths reported in the monthly PDE/ISC bulletins and that the CMT solutions are not necessarily optimal in their depth estimates.

Key Words: Regional Wave Propagation, Pokhran Test Site, Tibetan Plateau, GT10, ISC/REB Bulletin

Objectives: The principal objective of this paper is to present results of our on-going study on the path calibration for the entire Indian subcontinent to provide model-based P-wave travel times in the region. To accomplish this goal, it is necessary to establish a catalog of earthquakes with quantitative estimates of uncertainties in their ground truth locations. In general, nuclear explosions (when announced) and quarry blasts provide the best GT0 and GT2 locations respectively. It is, however, difficult to ascertain uncertainties in ground truth locations for earthquakes, especially at low magnitude ($M_w < 4.5$). For the majority of low magnitude earthquakes, depths are often not constrained to their true depths and events are poorly located due to a poor azimuthal coverage by recording stations. An objective of this paper is to demonstrate the effects of errors in depth on the uncertainties of ground truth epicentral locations of earthquakes in various parts of the world, particularly for earthquakes in the neighboring Tibetan Plateau.

We shall also summarize briefly crustal wave guides developed in various parts of the Indian subcontinent by local scientists and present an initial map showing the P_s velocity variation and thicknesses of the Moho discontinuity. So far, we have successfully developed crustal structure which can produce remarkable agreement for events recorded at Hyderabad (HYB) to distance of 12° covering the central India and Koyna regions. This model for the Peninsular India was also modified to fit detailed features observed in regional waveforms from events occurring in the Pokhran test site. Results from these preliminary studies are included in this report.

Research Issues: Unlike the former Soviet Union and the United States of America where calibration shots are plentiful and events are available to a GT of 0 to 2 km accuracy, there are a few data in our study region with similar precision except for the recent nuclear explosions in India and Pakistan in 1998 and in India in 1974. In general, establishing ground truth epicentral locations for earthquakes is difficult because the regionally varying crustal structure introduces errors in the reference earth model which together with the mis-identification of seismic phases shift the events from their true locations and depths. To correctly assign ground truth uncertainty on events, especially those of the magnitude (M_w) below 5 which are also recorded by a very few teleseismic stations, it is first necessary to establish the consistencies in events declared to have GTx (where x is accuracy in km) accuracy based on the criteria described at the pIDC (Yang and Romney, 1999). It must be determined when an event ($M_w < 5$) should be located using either the regionalized model or the iaspei91.

While for the large events located using teleseismic data, the error in depth causes only a trade-off in the origin time (Zhao and Helmberger, 1991), the small events appear to move significantly away from the ISC locations when they are located after establishing their depths and regional models. Thus, knowing the depth well is important in establishing the ground truth locations. Mislocation of depths for seismic events have been encountered in many regions of the world, for example in central Asia (Woods et al., 1998), in the Hindu-Kush (Zhao and Helmberger, 1991; Saikia et al., 1996; Zhu et al., 1997), Egypt and the Western Mediterranean (Thio et al., 1999), and in northeast India (Saikia, Zhu and Helmberger, 1997). In the following paragraphs, we cite further analysis of results from various studies illustrating that depths for small events need to be determined before they are located to assign any ground truth accuracy.

Research Accomplished:

Crust-Mantle Structure of the Indian Peninsula:

We are continuing our literature survey of available crustal models published by various in-country scientists in India (Gabriel and Kuo, 1966; Kaila et al., 1968, 1987; Bhattacharya, 1971; 1981; Dube et al., 1973; Dube and Bhayana, 1974 and others) in various parts of the Indian Peninsula. These studies are based on the travel times of P_g , P^* and P_n waves observed from shallow earthquakes with epicenters in Himalaya, analysis of dispersion in surface waves, and deep seismic sounding (DSS) data. We are in the process of scanning these various profiles and making them available in the geophysical database. These studies suggest that the thickness of the Moho varies between 40 and 45 km. The thickness of the upper crust has a thickness of about 15 km (P-wave velocity reaching 6.3 km/sec) and the lower crust

often consisting of two layers of velocities 6.6-6.9 km/s and 7.3-7.4 km/s. There are several other studies extending towards the northeast India beyond the Indian Peninsula towards the east (Kaila *et al.*, 1992; Kayal and Zhao, 1998; Mukhopadhyay and Krishna, 1991; Mukhopadhyay *et al.*, 1997; Singh, 1987). These studies also include refraction and wide-angle reflection data with profiles as long as 140 to 180 km. The path to the east includes the west Bengal basin, which starts west of Bangladesh and extends to northeast India. Within the basin structure, the refraction and wide-angle reflection data indicate presence of prominent refractors (velocities 1.7-2.1 km/s, 2.7-3.2 km/s, 3.7-4.2 km/s and 4.6-5.3 km/s) overlying the crystalline basement with a velocity of 5.8-6.2 km/s. In general, depth to the basement increases from west to east with a maximum depth of around 10 to 11 km at the extreme parts of the east-west trending two profiles where data were collected (Kaila *et al.*, 1992). The depth of the Moho discontinuity is reported to be highly variable, say 36 to 26 km along one profile and 32 to 34 km along the other profile. The region where these profiles were run is highly seismic and earthquakes occurring in this region will have variations in the travel times due to this type of variation in the crustal structure. Figure 1 shows a preliminary summary of these studies which show the various estimates of Pn velocities and the thickness of the Moho interface across the Indian Peninsula.

Epicentral Locations for Small Events ($M_w < 5$) and Depth Accuracy:

Central Asia: Figure 2 shows locations of 26 events for which depths were estimated using separate modeling techniques, such as matching of the surface-wave amplitude, modeling of P_n and surface-wave seismograms using regionalized velocity models, and modeling of teleseismic depth phases (pP and sP) using a crustal model appropriate for the source region. Figure 3a shows a comparison of depths of these events determined from the independent modeling of the P_n and teleseismic waves (Woods *et al.*, 1998), including the depths determined from a surface wave study (Patton, 1998). Dr. A. Valesco of Los Alamos National Laboratory relocated 17 of these events using regional and teleseismic travel times and a regional crustal model that was based on Dr. Walter Mooney's model of central Asia for both fixed (those obtained in our modeling studies) and free depths. Figure 3b shows relative shifts (Δr) of these new relocated epicenters from the EDR locations. For some events, for example events 7 and 16, moved away significantly from the EDR locations for the free depths.

Tibet: Figure 4 shows locations of 49 Tibetan earthquakes, relocated using an effective method developed by Zhu (1998) which does not require an *a priori* velocity model. It starts with a one-layer crustal model and first P arrival timings recorded by stations of a local network like those deployed during the PASSCAL experiments. Figure 5a shows hand-picked timings used for P and S waves plotted as a function of epicentral distances based on the ISC source locations and origin times. This data set consists of 363 P picks and 267 S picks. The large scatter is mostly attributable to the unreliable locations and origin times of the ISC catalog. The scheme used to relocate these events is based on an optimization problem in which the best location is obtained by iteratively minimizing the root-mean-squared value of the travel-time residuals (Zhu, 1998). The crustal model is updated and events are relocated until a global minimum is found. Figure 5b shows the travel times after relocation. Of the 49 relocated events, 7 events (squares, Table 1) satisfy the criteria for GT10 events (Yang and Romney, 1999) i.e., they have been recorded by at least 5 stations (actually > 5) within 3° and the largest azimuthal gaps between the stations within 5° is less than 180° . In Figure 6, we compare depths of the ISC and relocated depths for the events and shifts in their epicentral locations relative to the ISC locations as a function of M_w , showing that the events indeed moved by about 33 km. Two events which were poorly located in the ISC bulletin due to poor signal-to-noise ratio moved by more than 300 km from the ISC locations. Of these two, one qualified as a GT10 event and moved by about 650 km. ISC located this event using 8 stations of which 5 stations were within an array located at 9.5 - 10.5° away all lying within an azimuthal aperture of 2° . Actually the final iteration moved the event from the location 31.929° N lat and 94.465° E lon to 27.4° N lat and 97.0° E lon, reducing the RMS from 0.98s to 0.81s. Adding the regional stations not only increased the number of the stations, they also improved the azimuthal coverage. For 5 of the GT10 events, the ISC used picks from many stations distance ranging from 5° to all ranges. Although these stations provided good azimuthal coverage, relocations using augmented regional travel time picks and regionalized

model moved these events up to 20 km from the ISC locations.

Regional Seismogram Modeling

Central India: Our previous report (Saikia et al., 1998) discusses modeling of regional seismograms recorded at HYB from the Koyna region in south western India. To further calibrate the model towards northern India, we applied regional modeling approach to the HYB waveform from an earthquake (M_w 5.8, May 21, 1997) in central India. This event was recorded at many teleseismic stations. Before the path calibration, we have successfully modeled the teleseismic vertical and radial P waves using the inversion to retrieve source mechanism including the depth of this event (Figure 7). We also used this depth to invert the regional broadband seismograms at HYB located at a distance of 645 km (Figure 8, shows synthetics from both regional and teleseismic focal mechanism). Both solutions fit the data, shown in the upper seismograms, well, especially the S and surface waves. The regional solution produces a better fit to the P_{cl} waves. The calibrated model produces travel times of P, Rayleigh and Love waves consistent with the recorded seismograms.

Northwest India: We applied the same technique to model the source parameters of an earthquake which occurred on April 4, 1995 (M_w 4.3) near the Pokhran test site. Although located 100 km from the test site, this event is critical as it was recorded at both NIL in Pakistan and HYB. This is a small earthquake and its teleseismic depth phases could only be seen after processing the broadband seismograms to the equivalent WWSSN short-period records (Figure 9). In this way, we identified four teleseismic stations with observable depth phases (pP) which yielded a depth of 15 km, shallower than the ISC depth by 5 km and REB depth by 3 km. Using this depth, we inverted long-period HYB records (the only seismograms available) to estimate its focal mechanism and seismic moment (Figure 10a). As in the case of May 21 event, we could make the P wave onset times of Rayleigh and Love wave consistent with observations.

Pokhran to NIL: The next step was to model the regional seismograms recorded at NIL. Unlike the explosion data at NIL, this earthquake produced surface wave dispersion and some aspects of these surface waves motivated us to adjust the central India crustal model. The model that we have developed has a 7 km thick layer with lower surface wave velocities for P and S waves. A similar model was also determined at LLNL (Dr. W. R. Walter, personal communication) which has a thickness of about 4 km. Our model predicts recorded seismograms and travel times of P waves within a second (Figure 10b). This crustal model was used to generate the surface waves recorded at NIL from the Indian explosion with its source represented by the displacement potential (Figure 11).

Conclusions and Recommendations: We have presented results illustrating that accurate depths are necessary for establishing ground truth locations of small magnitude earthquakes ($M_w < 5$). A review of many studies demonstrates that errors in depth primarily trade off with the origin times for large events ($M_w > 5.5$) which yield many teleseismic travel time picks for locations. Variations in the reference crustal model and errors in identification of depth phases result in mislocations of the small magnitude earthquakes presented in various catalogs. Simultaneous inversion of regional crustal structure and travel-time picks of P and S waves of many earthquakes helps to yield good quality locations for earthquakes located within some local network. The locations and crustal structure can be optimized provided that depths for the chosen earthquakes are known by some other independent means before they are used in the analysis. Data collected from PASSCAL experiments of similar arrays can provide the necessary data to establish catalog of high-grade ground truth locations for earthquakes in various regions as we have shown in this report for the Tibet Plateau. Presently, there is no PASSCAL data available from within the Indian sub-continent. So we have calibrated crustal model using earthquakes which are large in magnitude for which the ISC epicentral locations are likely to be adequate. These models may still suffer from some minimal error in the travel times because of the error in depths. The depth we determined for the earthquake of May 21, 1997 is only 1 km different than the ISC depth and so error in the travel time due to the depth error is expected to be negligible. The earthquake of April 4, 1995 is several km off the ISC depth and it is possible that the travel time of the P waves towards NIL is off by about a second. Our

recommendation for future study in this area is to archive teleseismic broadband and short-period array data from smaller earthquakes ($M_w < 5$) and systemically analyze short-period data for the depth phases so that they can be used in conjunction with establishing the ground truth locations.

References

- Bhattacharya, S. N. (1974). The crust-mantle structure of the Indian Peninsula from surface wave dispersion, *Geophys. J. R. Astr. Soc.*, 36, 273-283.
- Bhattacharya, S. N. (1981). Observation and inversion of surface wave group velocities across central India, *Bull. Seis. Soc. Am.*, 71, 1489-1501.
- Dube, R. K., J. C. Bhayan, and H. M. Cahudhury (1973). Crustal structure of the Peninsula India, *Pure and Applied Geophys.* 109, 1718-1727.
- Dube, R. K. and J. C. Bhayana (1974). Crustal structure in the Gangetic Plains of the Indian subcontinent from body waves, *Bull. Seis. Soc. Am.*, 64, 571-579.
- Gabriel, V. G. and J. T. Toro (1966). High Rayleigh wave phase velocities for the New Delhi, India-Lahore, Pakistani profile, *Bull. Seis. Soc. Am.*, 56, 1137-1145.
- Kaila, K. L., P. R. Reddy and H. Narain (1968). Crustal structure in the Himalyan foothills area of north India, from P wave data of shallow earthquakes, *Bull. Seis. Soc. Am.*, 58, 597-612.
- Kaila, K. L., P. R. K. Murty, D. M. Mall, M. M. Dixit and D. Sarkar (1987). Deep seismic soundings along Hiraapur-Mandla profile, central India, *Geophys. J. R. Astr. Soc.*, 89, 399-404.
- Kaila, K. L., P. R. Reddy, D. M. Mall, N. Venkateswarlu, V. G. Krishna, and A.S.S.R.S. Prasad (1992). Crustal structure of the west Bengal basin, India from deep seismic sounding investigations, *Geophys. J. Int.*, 111, 46-66.
- Kayal, J. R. and D. Zhao (1998). Three-dimensional seismic structure beneath the Shillong Plateau and Assam Valley, northeast India, *Bull. Seis. Soc. Am.*, 88, 667-676.
- Mukhopadhyay, M. and M. R. Krishna (1991). Gravity field and deep structure of the Bengal fan and its surrounding continental margins, northeast Indian Ocean, *Tectonophysics*, 186, 365-386.
- Mukhopadhyay, M., R. Chander and K. N. Khattri (1997). Crustal properties in the epicentral tract of the Great 1897 Assam earthquake, northeastern India, *Tectonophysics*, 283, 311-330.
- Patton, H. J. (1980). Bias in the CMT moment tensor for central Asian earthquakes: evidence from regional data, *J. Geophys. Res.* (Accepted).
- Saikia, C. K., L. Zhu and D. V. Helmberger (1997). Relevance of broadband instruments in northeast India for seismic hazard mitigation, Symposium on the Great Shillong Earthq, held Nov 18, 1997 in Shillong, India.
- Saikia, C. K., B. B. Woods, H-K. Thio, L. Zhu and D. V. Helmberger (1996). Path calibration, source estimation and regional discrimination for Middle East: An application to the Hindu-Kush Region, PL-TR-96-2069, Scientific Report #1, Phillips Lab, MA 130p.
- Singh, D. D. (1987). Crust and upper-mantle velocity structure beneath north and central India from phase and group velocity of Rayleigh and Love waves, *Tectonophysics*, 139, 187-203.
- Thio, H-K., X. Song, C. K. Saikia, D. V. Helmberger and B. B. Woods (1999) Seismic source and structure in the western Mediterranean using a sparse broadband network, *J. Geophys. Res.*, 104, B1, 845-861.
- Woods, B. B., C. K. Saikia and H-K. Thio (1998). Focal depths and source parameters for earthquakes in northwest China, Tech. Report to Los Alamos National Laboratory.
- Yang, Xiaoping and C. Romney (1999). pIDC ground truth events (GT) database, CMR Technical Report, CMR-99/15.
- Zhao, L. S and D. V. Helmberger (1991). Geophysical implications from relocations of Tibetan earthquakes: Hot lithosphere, *Geophys. Res. Lett.*, 18, 2205-2208.
- Zhu, L., D. V. Helmberger, C. K. Saikia and B. B. Woods (1997). Regional waveform calibration in the Pamir Hindu-Kush region, *J. Geophys. Res.*, 102, 22,799-22,813.
- Zhu, L. (1998). Nbbroadband waveform modeling and its application to the lithospheric structure of the Tibetan Plateau, Ph.D. Thesis, California Institute of Technology, 141p

Table 1. GT10 locations for 7 earthquakes in Tibetan Plateau
(satisfy criteria of pIDC, Yang and Romney, 1999)

Date	OT(sec) h:m:s	latitude °N	longitude °E	depth h_r km	M_w	m_b	ΔR km	ΔH km $isc(h)-h_r$
11/19/91	01:04:18.0	32.54	93.82	10.0	3.9	4.2	16.9	23.0
11/26/91	21:16:00.0	34.10	94.22	10.0	4.3	4.2	3.9	22.0
12/02/91	19:45:38.1	32.16	94.53	10.0	4.0	4.2	20.8	47.0
01/08/92	17:41:39.9	30.06	92.30	10.0	3.8	3.9	21.1	14.0
01/23/92	10:26:25.8	34.49	93.18	5.0	4.1	4.3	6.9	4.0
02/03/92	15:44:22.6	34.46	93.20	10.0	4.3	4.5	5.7	0.0
03/30/92	18:29:47.7	32.60	93.79	10.0	3.7	3.9	653.7	13.0

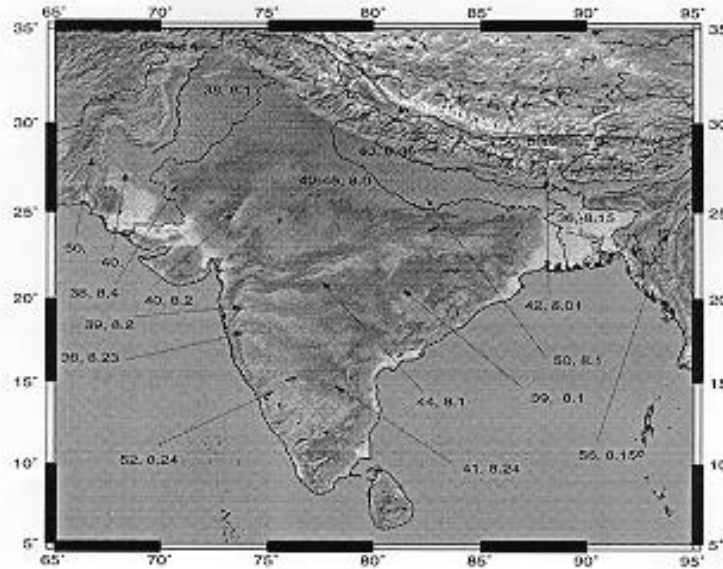


Figure 1. Map showing the variation of the Pn velocities and Moho thickness over the entire Indian subcontinent, including parts of Pakistan, Tibet, and Bangladesh.

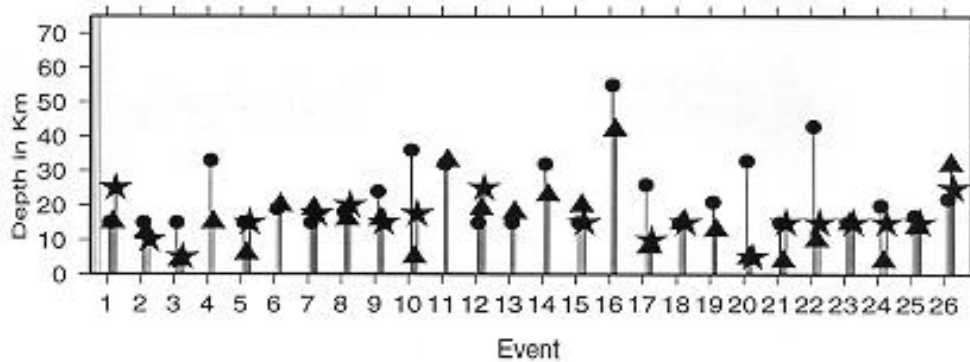


Figure 2. Comparison of depths determined by various methods: surface-waves (Patton, 1998), teleseismic (star) and broadband (triangle, Woods et al., 1998)

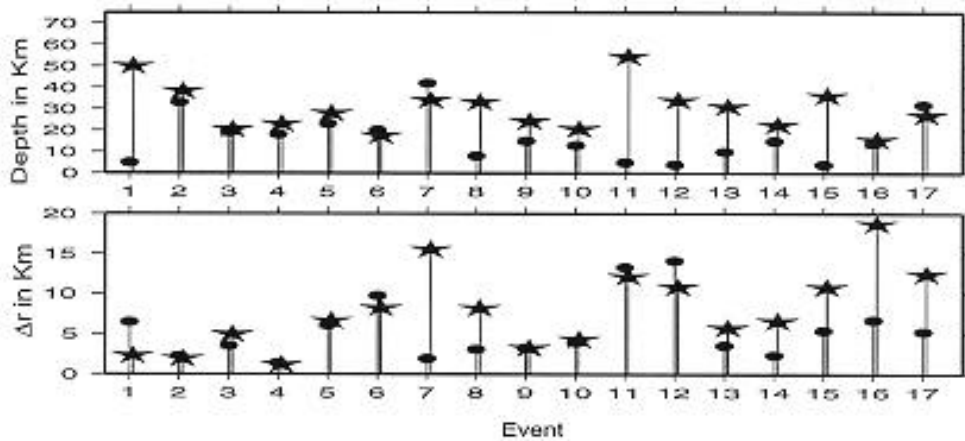


Figure 3. Top panels show comparison between the broadband modeling depths and the depths determined allowing depth to remain free in the location. Bottom panel shows movement of the epicenters for both fixed and free depths from the EDR locations.

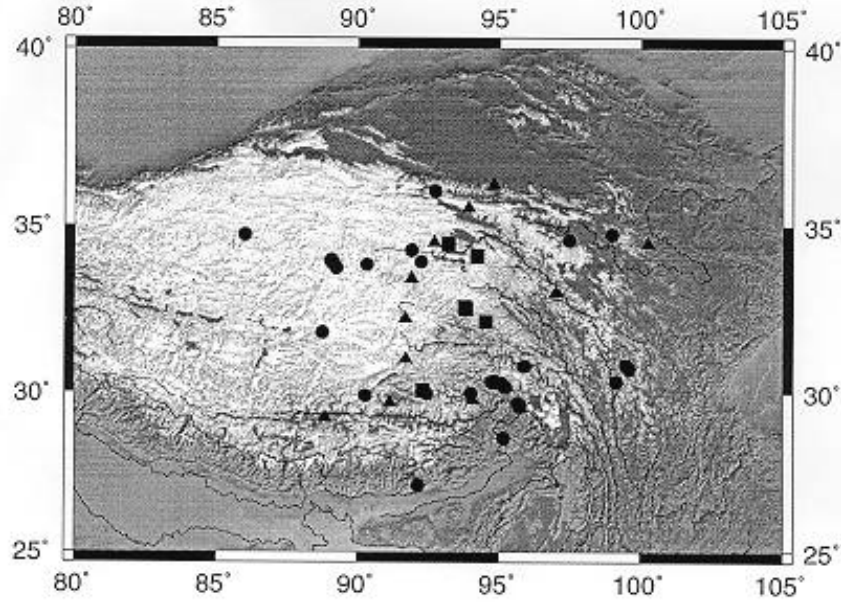


Figure 4. Map of the Tibetan Plateau showing the locations of stations (triangles) deployed during a PASSCAL experiment in 1991. Also shown are the relocated events (circles) and locations of seven GT10 events (squares).

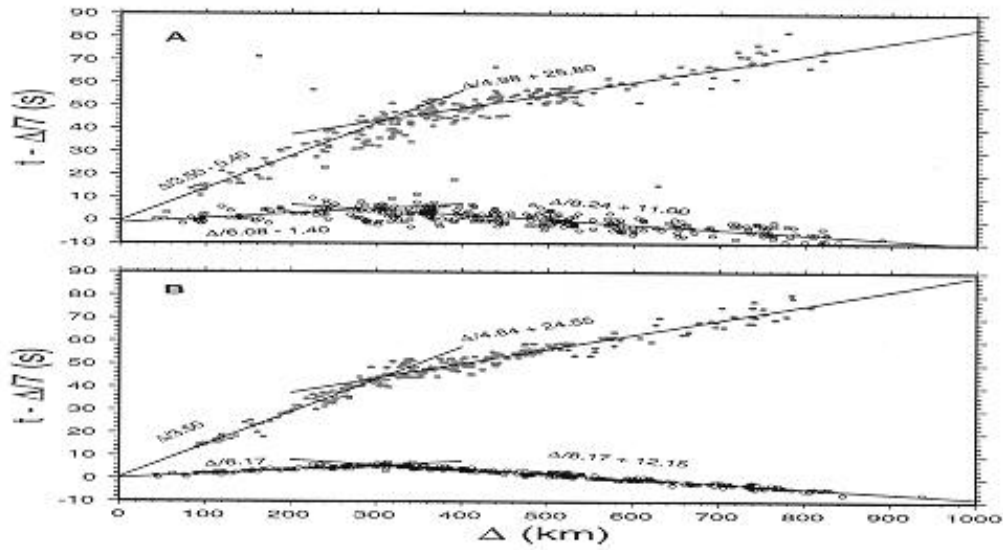


Figure 5A. Shows first P (open circles) and S (gray dots) arrival times as a function of epicentral distance using the ISC source locations and origin times. (B) shows travel times after relocations. The velocities of Pn, Pg, Sn and Sg are presented from the relocation study next to their branches (taken from Zhu, 1998).

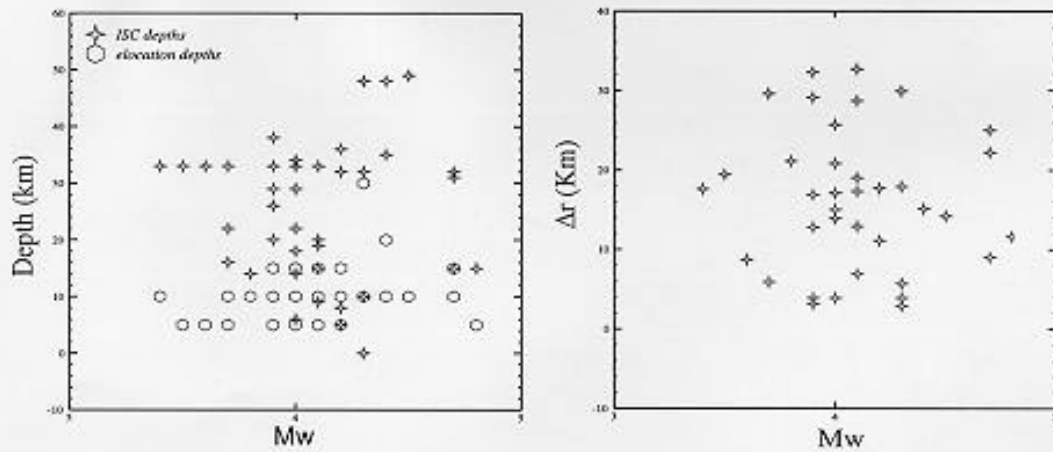


Figure 6. Left panel shows comparison of depths after relocations (open circles) and those reported in the ISC catalog. The majority of events have moved to shallow depths. Right panel shows the relative movement of these events from the ISC's epicentral locations (both panels use data presented in Tables 3.2 and 3.4 given in Zhu (1998)).

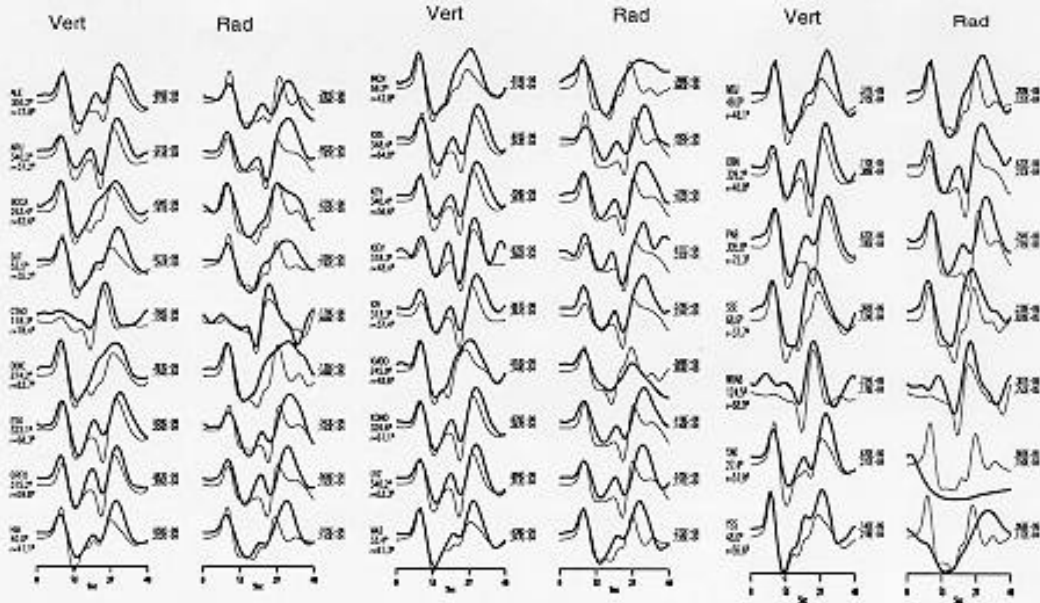


Figure 7. Comparison between data and synthetic seismograms using focal mechanism solution obtained using grid-search technique and both vertical and radial components. The thick waveforms are the recorded data and those in thin lines are synthetics computed using Haskell propagator matrices. We used the same receiver crust for all 27 stations. The peak amplitude of the data should be multiplied by a factor of 100. Station name, azimuth and distance in degrees are printed to the left of the vertical seismograms.

Modeling of Regional Seismograms at HYB of May 21, 1997 Earthquake (OT: 22H51m28.1s)

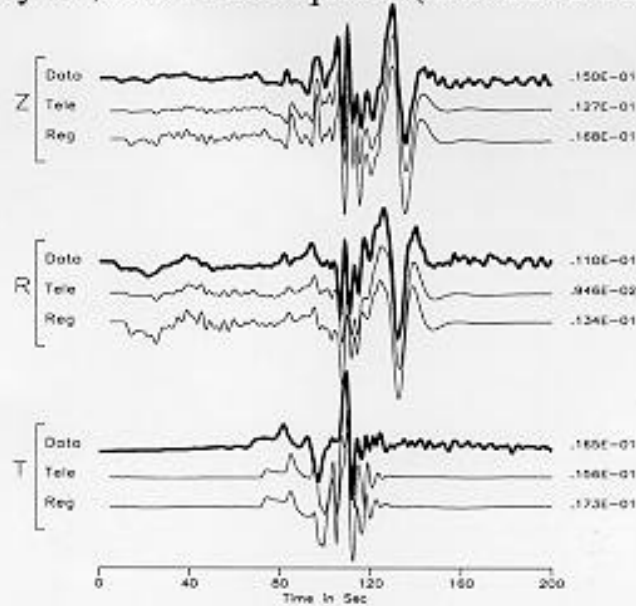


Figure 8. Comparison of data vs synthetic seismograms computed for the teleseismic and regional focal mechanism. A seismic moment of 5.88×10^{24} dyne-cm ($M_w=5.9$) and depth of 35 km were used. Note the agreement in peak amplitudes,

Raw Data vs. WWSSN-SP Simulation

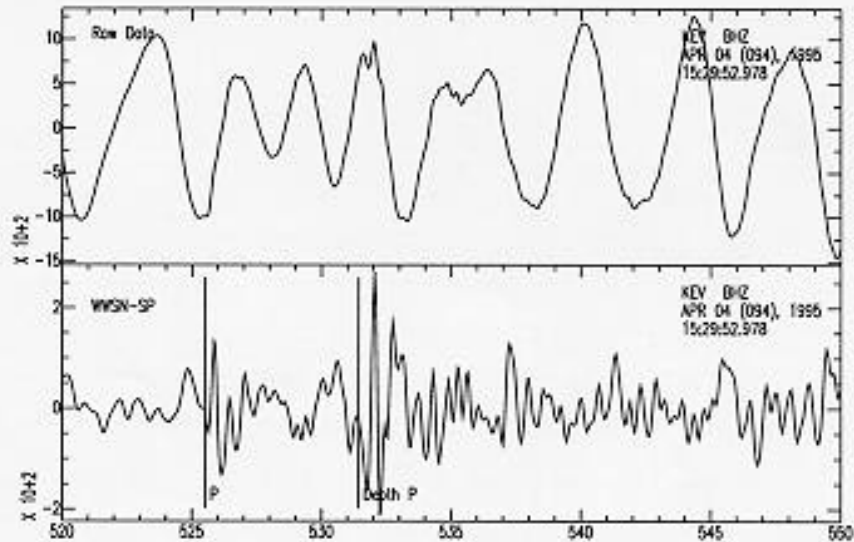


Figure 9. The upper seismogram is the recorded broadband waveform at KEV from the April 4, 1995 earthquake (M_w 4.3) near Pokhran test site. The bottom waveform is a simulation of raw data after convolving with a Wood-Anderson seismogram. Note the depth phase relative to P onset.

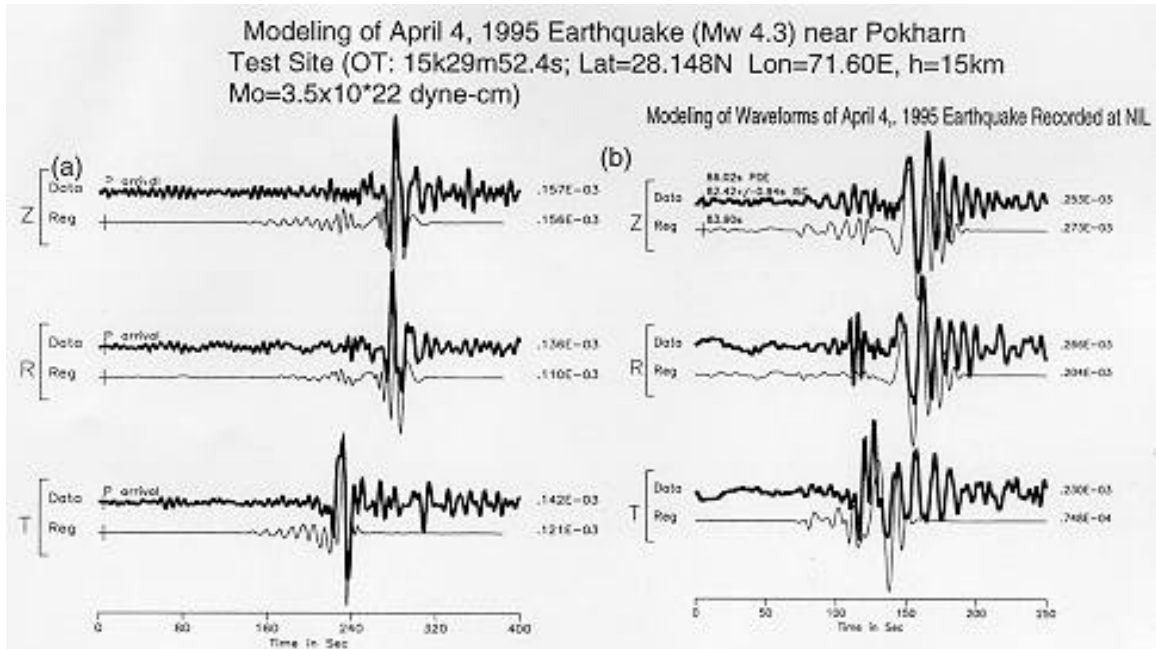


Figure 10. (a) Comparison between data and synthetic waveforms recorded at HYB station. Focal mechanism was obtained using grid-search technique using F-K green's functions computed at a depth of 15 km obtained by modeling depth phases shown in Figure 10. The recorded seismograms are shown by thick lines. (b) Modeling of data at NIL. Crustal model was developed from HYB model to produce dispersion observed in recorded data.

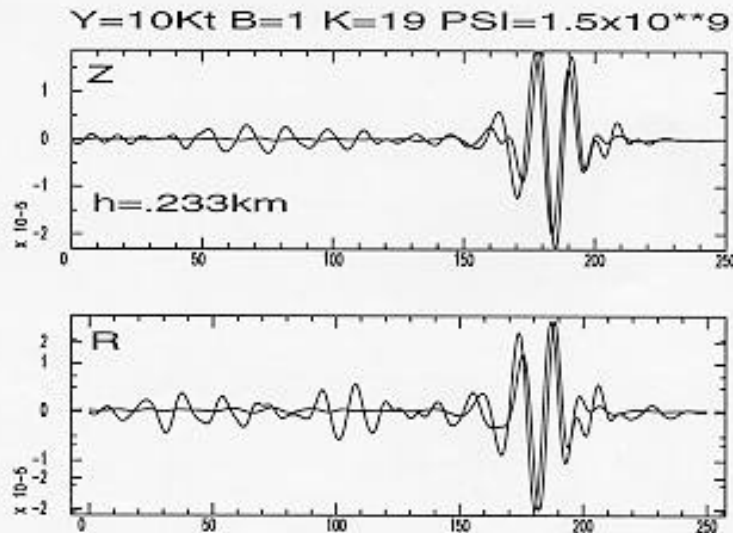


Figure 11. Modeling of Indian nuclear explosion data using the crustal model slightly modified from HYB. The NIL model developed in Figure 11b produces additional dispersion in the surface waves. The top layer is about 4 km thick, 3 km shallower than the model developed for the path in Figure 11b. The source function is represented by a reduced displacement potential and modeling is valid for the 0.05-0.2 Hz frequency range.